Chapter 19
Transmission Losses

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Introduction

Streams in natural channels in arid and semiarid regions are usually ephemeral. Flow is occasional and follows storms, which are infrequent. When flood flows occur in normally dry stream channels, the volume of flow is reduced by infiltration into the bed, the banks, and possibly the flood plain. These losses to infiltration, called transmission losses, reduce not only the volume of the hydrograph, but also the peak discharge.

This chapter describes a procedure for estimating the volume of runoff and peak discharge for ephemeral streams; it can be used with or without observed inflow-outflow data. If available, observed inflow-outflow data can be used to derive regression equations for the particular channel reach. Procedures based on the derived regression equations enable a user to determine prediction equations for similar channels of arbitrary length and width.

Also presented are procedures for estimating parameters of the prediction equations in the absence of observed inflow-outflow data. These procedures are based on characteristics of the bed and bank material. Approximations for lateral inflow and out-of-bank flow are also presented.

Assumptions and Limitations

Assumptions

The methods described in this chapter are based on the following assumptions:

1. Water is lost in the channel; no streams gain water.
2. Infiltration characteristics and other channel properties are uniform with distance and width.
3. Sediment concentration, temperature, and antecedent flow affect transmission losses, but the equations represent the average conditions.
4. The channel reach is short enough that an average width and an average duration represent the width and duration of flow for the entire channel reach.
5. Once a threshold volume has been satisfied, outflow volumes are linear with inflow volumes.
6. Once an average loss rate is subtracted and the inflow volume exceeds the threshold volume, peak rates of outflow are linear with peak rates of inflow. Moreover, the rate of change in outflow peak discharge with changing inflow peak discharge is the same as the rate of change in outflow volume with changing inflow volume.

7. Lateral inflow can be either lumped at points of tributary inflow or uniform with distance along the channel.

8. For volume and peak discharge calculations, lateral inflow is assumed to occur during the same time as the upstream inflow.

Limitations

The main limitations of the procedures are:

1. Hydrographs are not specifically routed along the stream channels; predictions are made for volume and peak discharge.
2. Peak flow equations do not consider storage attenuation effects or steepening of the hydrograph rise.
3. Analyses on which the procedures are based represent average conditions or overall trends.
4. Influences of antecedent flow and sediment concentration in the streamflow have not been quantified.
5. Estimates of effective hydraulic conductivity in the streambed are empirically based and represent average rates.
6. Peak discharge of outflow is decreased by the average loss rate for the duration of flow.
7. Procedures for out-of-bank flow are based on the assumption of a weighted average for the effective hydraulic conductivity.

Symbols and Notation

Upstream Inflow

D = duration of inflow (hours)
P = inflow volume (acre-feet)
p = peak rate of inflow (cubic feet per second)

Lateral Inflow

Q_L = lateral inflow volume (acre-feet per mile)
q_L = peak rate of lateral inflow (cubic feet per second per foot)

Outflow

Q(x,w) = outflow volume (acre-feet)
q(x,w) = peak rate of outflow (cubic feet per second)

Channel Reach

D = duration of streamflow (hours)
K = effective hydraulic conductivity (inches per hour)
V = total available storage volume of alluvium in the channel reach (acre-feet)
w = average width of flow (feet)
x = length of reach (miles)

Prediction Equations (Parameters)

a = regression intercept for unit channel (acre-feet)
a(D) = regression intercept for unit channel with a flow of duration D (acre-feet)
a(x,w) = regression intercept for a channel reach of length x and width w (acre-feet)
b = regression slope for unit channel
b(x,w) = regression slope for a channel reach of length x and width w
k = decay factor $(\text{foot-miles})^{-1}$
k(D,P) = decay factor for unit channel with a flow duration D and volume P $(\text{foot-miles})^{-1}$
P_o = threshold volume for a unit channel (acre-feet)
$P_o(x,w)$ = threshold volume for a channel reach of length x and width w (acre-feet)

The simplified procedures are summarized here; additional details and derivations are given in the appendices. Methods have been developed for two situations: (1) when observed inflow-outflow data are available and (2) when no observed data are available.

Summary of Procedure

The prediction equation for outflow volume, without lateral inflow, is

$$Q(x,w) = \begin{cases} 0 & P \leq P_o(x,w) \\ a(x,w) + b(x,w)P & P > P_o(x,w), \end{cases} \tag{19–1}$$

where the threshold volume is

$$P_o(x,w) = \frac{-a(x,w)}{b(x,w)}. \tag{19–2}$$

The corresponding equation for peak discharge is

$$q(x,w) = \begin{cases} 0 & Q(x,w) = 0 \\ \frac{12.1}{D}(a(x,w) & Q(x,w) > 0, \\ \quad -[1-b(x,w)]P) & \\ \quad + b(x,w)p & \end{cases} \tag{19–3}$$

where 12.1 converts from acre-feet per hour to cubic feet per second.

If lateral inflow is uniform, the volume equation becomes

$$Q(x,w) = \begin{cases} 0 & b(x,w)P + \frac{Q_L}{kw}[1-b(x,w)] \leq -a(x,w) \\ a(x,w) + b(x,w)P + \frac{Q_L}{kw}[1-b(x,w)]. & \end{cases} \tag{19–4}$$

The corresponding equation for peak discharge is

$$q(x,w) = \begin{cases} 0 & Q(x,w) = 0 \\ \frac{12.1}{D}(a(x,w) - [1-b(x,w)]P) & \\ \quad + b(x,w)p + \frac{q_L(5{,}280)}{kw} & \\ \quad [1-b(x,w)]. & \end{cases} \tag{19–5}$$

The factor 5,280 converts cubic feet per second per foot to cubic feet per second per mile. Derivations and background information are found in Appendix 1.

For a channel reach with only tributary lateral inflow, equations 19–1 and 19–3 would be applied on the tributary channel and the main channel to the point of tributary inflow. Then the sum of the outflows from these two channel reaches would be the inflow to the lower reach of the main channel.

The procedures described by equations 19–1, 19–3, 19–4, and 19–5 require that the upstream inflow and lateral inflow along the channel reach be estimated by use of procedures described in Chapter 10. Peak rates and durations are estimated by use of procedures described in Chapter 16.

Estimating Parameters From Observed Inflow-Outflow Data

If one assumes a channel reach of length x and average width w, then n observations on P_i and Q_i (without lateral inflow) can be used to estimate the parameters in equation 19–1. Parameters of the linear regression equation can be estimated as

$$b(x,w) = \frac{\sum_{i=1}^{n}(Q_i - \overline{Q})(P_i - \overline{P})}{\sum_{i=1}^{n}(P_i - \overline{P})^2} \tag{19–6}$$

and

$$a(x,w) = \overline{Q} - b(x,w)\overline{P}, \tag{19–7}$$

where $\overline{Q}$ is the mean outflow volume and $\overline{P}$ is the mean inflow volume. Alternative formulas recommended for computation are

$$\sum_{i=1}^{n}(Q_i - \overline{Q})(P_i - \overline{P}) = \frac{n\sum_{i=1}^{n}P_iQ_i - \left(\sum_{i=1}^{n}P_i\right)\left(\sum_{i=1}^{n}Q_i\right)}{n} \tag{19–8}$$

and

$$\sum_{i=1}^{n}(P_i - \overline{P})^2 = \frac{n\sum_{i=1}^{n}P_i^2 - \left(\sum_{i=1}^{n}P_i\right)^2}{n}. \tag{19–9}$$

Linear regression procedures are available on most computer systems and on many hand-held calculators. Constraints on the parameters are

$$a(x,w) < 0$$

and

$$0 \leq b(x,w) \leq 1.$$

When one or both of the constraints are not met, the following procedure is suggested:

1. Plot the observed data on rectangular coordinate paper: P_i on the X-axis and Q_i on the Y-axis.
2. Plot the derived regression equation on the graph with the data.
3. Check the data for errors (events with lateral inflow, computational errors, etc.). Pay particular attention to any data points very far from the regression line, especially those points that may be strongly influencing the slope or intercept.
4. Correct data points that are in error; remove points that are not representative.
5. Recompute the regression slope and intercept using equations 19–6 to 19–9 and the corrected data.

A great deal of care and engineering judgment must be exercised in finding and eliminating errors from the set of observed inflow-outflow observations.

Unit Channels

A unit channel is defined as a channel of length x = 1 mi and width w = 1 ft. Parameters for the unit channel are required to compute parameters for channel reaches with arbitrary length and width. The unit channel parameters are computed by the following equations:

$$k = -\frac{\ln b(x,w)}{x\,w} \qquad \textbf{(19–10)}$$

$$b = e^{-k} \qquad \textbf{(19–11)}$$

$$a = \frac{a(x,w)(1 - b)}{[1 - b(x,w)]}, \qquad \textbf{(19–12)}$$

where a(x,w) and b(x,w) are the regression parameters derived from the observed data. In this case, the length x and width w are fixed known values. Particular care must be taken to maintain the maximum number of significant digits in determining k, b, and a. Otherwise, significant round-off errors can result.

Reaches of Arbitrary Length and Width

Given parameters for a unit channel, parameters for a channel reach of arbitrary length x and arbitrary width w are computed by the following equations:

$$b(x,w) = e^{-kxw}, \qquad \textbf{(19–13)}$$

$$a(x,w) = \frac{a}{1 - b}[1 - b(x,w)], \qquad \textbf{(19–14)}$$

$$P_o(x,w) = \frac{-a(x,w)}{b(x,w)}. \qquad \textbf{(19–2)}$$

Estimating Parameters in the Absence of Observed Inflow-Outflow Data

When inflow-outflow data are not available, an estimate of effective hydraulic conductivity is needed to predict transmission losses. Effective hydraulic conductivity, K, is the infiltration rate averaged over the total area wetted by the flow and over the total duration of flow. Because effective hydraulic conductivity represents a space-time average infiltration rate, it incorporates the influence of temperature, sediment concentration, flow irregularities, errors in the data, and variations in wetted area. For this reason, it is not the same as the saturated hydraulic conductivity for clear water under steady-state conditions.

Analysis of observed data resulted in equations of the form

$$a(D) = -0.00465KD \qquad \textbf{(19–15)}$$

for the unit channel intercept and

$$k(D,P) = -1.09 \ln\left[1.0 - 0.0545\frac{KD}{P}\right] \qquad \textbf{(19–16)}$$

for the decay factor on ungaged reaches. Given values of a and k from equations 19–15 and 19–16, equations 19–13, 19–14, and 19–2 are used to compute parameters for a particular x and w.

Derived relationships between bed material characteristics, effective hydraulic conductivity, and the unit channel parameters a and k are shown in table 19–1. These data can be used to estimate parameters for ungaged channel reaches.

Table 19–1.—Relationships between bed material characteristics and parameters for a unit channel (average antecedent conditions)

Bed material group	Bed material characteristics	Effective hydraulic conductivity,[1] K	Unit channel parameters	
			Intercept,[2] a	Decay factor,[3] k
		in/hr	*acre-ft*	*(ft-mi)$^{-1}$*
1 Very high loss rate	Very clean gravel and large sand	>5	<-0.023	>0.030
2 High loss rate	Clean sand and gravel, field conditions	2.0–5.0	-0.0093 to -0.023	0.0120 to 0.030
3 Moderately high loss rate	Sand and gravel mixture with low silt-clay content	1.0–3.0	-0.0047 to -0.014	0.0060 to 0.018
4 Moderate loss rate	Sand and gravel mixture with high silt-clay content	0.25–1.0	-0.0012 to -0.0047	0.0015 to 0.0060
5 Insignificant to low loss rate	Consolidated bed material; high silt-clay content	0.001–0.10	-5×10^{-6} to -5×10^{-4}	6×10^{-6} to 6×10^{-4}

[1] See Appendix 3 for sources of basic data.
[2] Values are for unit duration, D = 1 hr. For other durations, $a(D) = -0.00465KD$.
[3] Values are for unit duration and volume, D/P = 1. For other durations and volumes,

use $k(D,P) = -1.09 \ln \left[1.0 - 0.00545\frac{KD}{P}\right]$.

Summary of Parameter Estimation Techniques

Suggested procedures for use when observed data are available are summarized in table 19–2. Procedures for use on ungaged channel reaches are summarized in table 19–3. Again, whatever procedure is used, the parameter estimates must satisfy the constraints $a(x,w) < 0$ and $0 \leq b(x,w) \leq 1$.

Table 19–2.—Procedures to use when observed inflow-outflow data are available

Step	Source	Result
1. Perform regression analysis	Eqs. 19–6, 19–7, 19–2	Prediction equations for the particular reach
2. Derive unit channel parameters	Eqs. 19–10 to 19–12	Unit channel parameters
3. Calculate parameters	Eqs. 19–13, 19–14, 19–2	Parameters of the prediction equations for arbitrary x and w

Table 19–3.—Procedures to use when no observed inflow-outflow data are available

Step	Source	Result
1. Estimate inflow	Hydrologic analysis	Mean duration of flow, D, and volume of inflow, P
2. Identify bed material	Table 19–1	Effective hydraulic conductivity, K
3. Derive unit channel parameters	Eqs. 19–15, 19–16, 19–11	Unit channel parameters
4. Calculate parameters	Eqs. 19–13, 19–14, 19–2	Parameters of the prediction equations for arbitrary x and w

Examples

The following examples illustrate application of the procedures for several cases under a variety of circumstances. As in any analysis, it was impossible to consider all possible combinations of circumstances, but the examples presented here should provide an overview of useful applications of the procedures. Use of these procedures requires judgment and experience. At each step of the process, care should be taken to ensure that the results are reasonable and consistent with sound engineering practice.

Example 1. No Lateral Inflow or Out-of-Bank Flow

Given: A channel reach of length x = 5.0 mi, of average width w = 70 ft, and with bed material consisting of sand and gravel with a small percentage of silt and clay. Assume a mean flow duration D = 4 hr and a mean inflow volume of P = 34 acre-ft.

Find: The prediction equations for the channel reach. Estimate the outflow volume and peak for an inflow P = 50 acre-ft and p = 1,000 cfs.

Case 1. Observed Inflow-Outflow Data

Observed Inflow-Outflow Data (acre-ft)

P_i	20.	100.	25.	10.	15.	$\overline{P} = 34$
Q_i	6.0	75.	9.0	0.1	2.5	$\overline{Q} = 18.52$

Solution: Follow the procedure outlined in table 19–2, Step 1, for x = 5.0 mi and w = 70 ft.

$$b(x,w) = \frac{\Sigma(Q_i - \overline{Q})(P_i - \overline{P})}{\Sigma(P_i - \overline{P})^2} = 0.850$$

$$\begin{aligned} a(x,w) &= \overline{Q} - b(x,w)\overline{P} \\ &= 18.52 - 0.850(34) = -10.38 \text{ acre-ft} \end{aligned}$$

$$P_o(x,w) = \frac{-a(x,w)}{b(x,w)} = \frac{10.38}{0.850} = 12.21 \text{ acre-ft}$$

Substituting these values in equation 19–1, the prediction equation for volume is

$$Q(x,w) = \begin{cases} 0 & P \leq 12.21 \\ -10.38 + 0.850P & P > 12.21 \end{cases}$$

and the prediction equation (from equation 19–3) for peak discharge is

$$q(x,w) = \begin{cases} 0 & Q(x,w) = 0 \\ -31.4 - 0.454P + 0.850p & Q(x,w) > 0. \end{cases}$$

For an inflow volume P = 50 acre-ft and an inflow peak rate p = 1,000 cfs, the predicted outflow volume is

$$Q(x,w) = -10.38 + 0.850(50) = 32.1 \text{ acre-ft}$$

and the predicted peak rate of outflow is

$$\begin{aligned} q(x,w) &= -31.4 - 0.454(50) + 0.850(1{,}000) \\ &= 796 \text{ cfs.} \end{aligned}$$

Case 2. No Observed Inflow-Outflow Data

Solution: Follow the procedures outlined in table 19–3.

From table 19–1, estimate K = 1.0 in/hr, with D = 4.0 hr, P = 34 acre-ft. So

$$a = -0.00465KD = -0.01860 \text{ acre-ft},$$

$$\begin{aligned} k &= -1.09 \ln\left[1.0 - 0.00545\frac{KD}{P}\right] \\ &= 0.000699 \text{ (ft-mi)}^{-1}, \end{aligned}$$

and

$$b = e^{-k} = e^{-0.000699} = 0.999301$$

are the unit channel parameters. From equations 19–13, 19–14, and 19–2, the parameters for the given reach with x = 5.0 mi and w = 70 ft are

$$\begin{aligned} b(x,w) &= e^{-kxw} = e^{-(0.000699)(5.0)(70)} \\ &= 0.783, \end{aligned}$$

$$\begin{aligned} a(x,w) &= \frac{a}{1-b}[1 - b(x,w)] \\ &= \frac{-0.01860}{(1 - 0.999301)}[1 - 0.783] \\ &= -5.78 \text{ acre-ft}, \end{aligned}$$

and

$$P_o(x,w) = \frac{-a(x,w)}{b(x,w)}$$
$$= -\frac{(-5.78)}{0.783} = 7.38 \text{ acre-ft.}$$

The prediction equation for the volume is

$$Q(x,w) = \begin{cases} 0 & P < 7.38 \\ -5.78 + 0.783P, & P > 7.38 \end{cases}$$

and the prediction equation for peak discharge is

$$q(x,w) = \begin{cases} 0 & Q(x,w) = 0 \\ -17.5 - 0.656P \\ \quad + 0.783p & Q(x,w) > 0. \end{cases}$$

For an inflow volume of $P = 50$ acre-ft and an inflow peak rate of $p = 1{,}000$ cfs, the predicted outflow volume is

$$Q(x,w) = -5.78 + 0.783(50) = 33.4 \text{ acre-ft,}$$

and the predicted peak rate of outflow is

$$q(x,w) = -17.5 - 0.656(50) + 0.783(1{,}000)$$
$$= 733 \text{ cfs.}$$

This example illustrates application of the procedures with and without observed data when flow is within the channel banks and there is no lateral inflow. The next example is for the same channel reach but is based on assumption of uniform lateral inflow between the inflow and outflow stations.

Example 2. Uniform Lateral Inflow

Given: The channel reach parameters from Example 1 and a lateral inflow of 21.3 acre-ft at a peak rate of 500 cfs. Assume the lateral inflow is uniformly distributed.

Find: The volume of outflow and peak rate of outflow if $P = 50$ acre-ft and $p = 1{,}000$ cfs.

Solution: Compute the lateral rates as follows:

$$Q_L = \frac{21.3 \text{ acre-ft}}{5.0 \text{ mi}} = 4.26 \text{ acre-ft/mi}$$

and

$$q_L = \frac{500 \text{ cfs}}{(5.0 \text{ mi})(5{,}280 \text{ ft/mi})} = 0.0189 \text{ cfs/ft.}$$

Using $a(x,w) = -5.78$, $b(x,w) = 0.783$, $k = 0.000699$, and $w = 70$ from Case 2 of Example 1 in equation 19–4, the result is

$$Q(x,w) = -5.78 + 0.783P + \frac{Q_L}{kw}(1 - 0.783)$$
$$= 52.3 \text{ acre-ft.}$$

The corresponding calculations for peak discharge of the outflow hydrograph (eq. 19–5) are

$$q(x,w) = -17.5 - 0.656P + 0.783p$$
$$+ \frac{q_L\,(5{,}280)}{kw}[1 - 0.783]$$
$$= 1{,}175 \text{ cfs.}$$

Example 3. Approximations for Out-of-Bank Flow

In this example, approximations for out-of-bank flow are described and discussed.

Given: A channel reach of length $x = 10$ mi and an average width of in-bank flow $w_1 = 150$ ft with in-bank flow up to a discharge of 3,000 cfs. Once the flow exceeds 3,000 cfs, out-of-bank flow rapidly covers wide areas. The bed material consists of clean sand and gravel, and the out-of-bank material is sandy with significant amounts of silt-clay.

Find: The outflow if the inflow is $P = 700$ acre-ft with a peak rate of $p = 4{,}000$ cfs. Assume the mean duration of flow is 12 hr and the total average width of out-of-bank flow is 400 ft. Also, estimate the distance downstream before the flow is back within the channel banks.

Solution: Using the procedures outlined in table 19–3, make the following calculations:

In-bank flow:

$w_1 = 150$ ft;

$K_1^* = 3.0$ in/hr.

Out-of-bank flow:

$w_2 = 400$ ft†;

$K_2^* = 0.5$ in/hr for width $w_2 - w_1$.

The weighted average for effective hydraulic conductivity is

$$K = \frac{w_1K_1 + (w_2 - w_1)K_2}{w_2} \qquad (19\text{–}17)$$

$$K = 1.44 \text{ in/hr.}$$

Using this average value of K, D = 12 hr, and P = 700 acre-ft, the unit channel parameters are

$$a = -0.00465KD = -0.08035 \text{ acre-ft,}$$

$$k = -1.09 \ln\left[1.0 - 0.00545\frac{KD}{P}\right] = 0.000147 \text{ (ft-mi)}^{-1},$$

and

$$b = e^{-k} = e^{-0.000147} = 0.99985.$$

Given the unit channel parameters and $w_2 = 400$ ft, the parameters for the channel reach are

$$b(x,w_2) = e^{-kxw_2} = e^{-(0.000147)(400)x} = e^{-0.0588x}$$

and

$$a(x,w_2) = \frac{a}{1-b}[1 - b(x,w_2)] = \frac{-0.08035}{(1 - 0.99985)}[1 - e^{-0.0588x}].$$

Now, estimate the distance downstream until flow is contained within the banks (from equation 19–3) as

$$q(x,w) = \frac{12.1}{D}(a(x,w) - [1 - b(x,w)]P) + b(x,w)p.$$

Use an upper limit as

$$q(x,w) = 3{,}000 \text{ cfs} \leqslant b(x,w)p = e^{-0.0588x}(4{,}000),$$

which means

$$e^{-0.0588x} \geqslant \frac{3{,}000}{4{,}000} = 0.75$$

$$x \leqslant -\frac{1.0}{0.0588}\ln 0.75 = 4.89 \text{ mi.}$$

Then a trial-and-error solution of the volume and peak discharge equations for various values of $x < 4.89$ mi produces a best estimate of $x = 3.6$ mi. Based on this value, the parameters are

$$b(3.6,w_2) = 0.809$$

and

$$a(3.6,w_2) = -102.3 \text{ acre-ft.}$$

Therefore, the predictions for $x = 3.6$ mi are

$$Q(3.6,w_2) = -102.3 + 0.809(700) = 464.0 \text{ acre-ft}$$

for the volume and

$$q(3.6,w_2) = -238.0 + 0.809(4{,}000) = 2{,}998 \text{ cfs}$$

for the peak rate. For distances beyond this point, the flow will be contained in the channel banks. The parameters for in-bank flow with a distance of x = 10.0 − 3.6 = 6.4 mi are

$$a = -0.00465KD = -0.1674 \text{ acre-ft,}$$

$$k = -1.09 \ln\left[1 - 0.00545\frac{KD}{P}\right] = 0.000461 \text{ (ft-mi)}^{-1},$$

and

$$b = e^{-k} = e^{-0.000461} = 0.99954$$

* *Average hydraulic conductivity from table 19–1.*

† *Includes width w_1.*

for K = 3.0, D = 12, and P = 464.0 acre-ft, which is the inflow from the upstream reach. With these unit channel parameters, the parameters for in-bank flow are

$$b(6.4,w_1) = e^{-kxw_1} = e^{-(0.000461)(6.4)(150)} = 0.642$$

and

$$\begin{aligned} a(6.4,w_1) &= \frac{a}{1-b}[1 - b(x,w_1)] \\ &= \frac{-0.1674}{(1 - 0.99954)}[1 - 0.642] \\ &= -130.3 \text{ acre-ft.} \end{aligned}$$

The predicted outflow is

$$\begin{aligned} Q(6.4,w_1) &= -130.3 + 0.642(464.0) \\ &= 167.6 \text{ acre-ft} \end{aligned}$$

for the volume and

$$\begin{aligned} q(6.4,w_1) &= -298.9 + 0.642(2{,}998) \\ &= 1{,}626 \text{ cfs} \end{aligned}$$

for the peak discharge. Therefore, the prediction is out-of-bank flow for about 3.6 mi and in-bank flow for 6.4 mi, with an outflow volume of 168 acre-ft and a peak discharge of 1,626 cfs.

This example illustrates the need for judgment in applying the procedure for estimating losses in out-of-bank flow. Care must be taken to ensure that transmission losses do not reduce the flow volume and peak to the point where flow is entirely within the channel banks. If this occurs, then the reach length must be broken into subreaches, as illustrated in this example.

Example 4. Transmission Losses Limited by Available Storage

In some circumstances, an alluvial channel could be underlain by nearly impervious material that might limit the potential storage volume in the alluvium (V) and thereby limit the potential transmission losses. Once the transmission losses fill the available storage, nearly all additional inflow will become outflow; the procedure is modified to predict and apply this secondary threshold volume, P_1.

Given: The channel reach in Example 1 with total available storage (maximum potential transmission loss) of V = 30 acre-ft. Given the volume equation from Case 1 of Example 1, compute equations to apply after the potential losses are satisfied. From Example 1, a(x,w) = −10.38 acre-ft, b(x,w) = 0.850, and $P_o(x,w)$ = 12.21 acre-ft.

Solution: The total losses are P − Q(x,w) computed as

$$\begin{aligned} P - [a(x,w) + b(x,w)P] = &-a(x,w) \\ &+ [1 - b(x,w)]P. \end{aligned}$$

Equating this computed loss to V and solving for the inflow volume predicts the inflow volume above which only the maximum alluvial storage is subtracted,

$$P_1 = \frac{V + a(x,w)}{1 - b(x,w)}.$$

For this example, this threshold inflow volume is 130.8 acre-ft. With this additional threshold, the prediction equation for outflow volume is modified to

$$Q(x,w) = \begin{cases} 0 & P \leq P_o(x,w) \\ a(x,w) + b(x,w)P & P_o(x,w) \leq P \leq P_1 \\ P - V & P > P_1. \end{cases} \tag{19–18}$$

For the example being discussed, the solution to this general equation is

$$Q(x,w) = \begin{cases} 0 & P \leq 12.21 \\ -10.38 + 0.850P & 12.21 \leq P \leq 130.8 \\ P - 30 & P > 130.8 \end{cases}$$

The slope of the regression line is equal to Q(x,w)/ $[P - P_o(x,w)]$, so an equivalent slope, once the available storage is filled, is $b_{eq} = (P - V)/[P - P_o(x,w)]$, which for this example is $b_{eq} = (P - 30)/(P - 12.21)$. For an inflow volume of P = 300 acre-ft and p = 3,000, the equivalent slope is b_{eq} = 0.938. Using the equivalent slope, the peak equation is

$$\begin{aligned} q(x,w) &= \frac{-12.1}{D}[P - Q(x,w)] + b_{eq}P \\ &= -90.75 + 0.938(3{,}000) = 2{,}723 \text{ cfs.} \end{aligned}$$

Therefore, the predicted outflow is Q(x,w) = 270 acre-ft and q(x,w) = 2,723 cfs.

If the storage limitation had been ignored, the original equations would have predicted an outflow volume of 245 acre-ft and a peak rate of outflow of 2,384 cfs. If a channel reach has limited available storage, the procedure should be modified, as it was in Example 4, to compute losses that do not exceed the available storage.

Summary

The examples presented illustrate the wide range of applications of the transmission loss procedures described in this chapter. The examples were chosen to emphasize some limitations and the need for sound engineering judgment. These concepts are summarized in table 19–4.

Table 19–4.—Outline of examples and comments on their applications

Example	Procedure	Special circumstances	Comments
1 (Case 1)	Table 19–2	Observed data available	Slope and intercept must satisfy the constraints
1 (Case 2)	Table 19–3	No observed data	Typical application
2	Table 19–3 Eqs. 19–4, 19–5	Uniform lateral inflow	Importance of lateral inflow demonstrated
3	Table 19–3 Eq. 19–17	Out-of-bank flow	Judgment required to interpret results
4	Table 19–2 Eq. 19–18	Limited available storage	Concept of equivalent slope used

Appendices

These appendices provide the reference material, derivations, and analyses of available data upon which the material presented in Chapter 19 is based. The basic procedure is outlined, and sources for additional information are provided.

Appendix 1—Derivation of Procedures for Estimating Transmission Losses When Observed Data Are Available

In much of the Southwestern United States, watersheds are characterized as semiarid with broad alluvium-filled channels that abstract large quantities of streamflow (Babcock and Cushing 1941; Burkham 1970a, 1970b; Renard 1970). These abstractions or transmission losses are important because streamflow is lost as the flood wave travels downstream, and thus runoff volumes are reduced. Although these abstractions are referred to as losses, they are an important part of the water balance. They diminish streamflow, support riparian vegetation, and recharge local aquifers and regional ground water (Renard 1970).

Simplified procedures have been developed to estimate transmission losses in ephemeral streams. These procedures include simple regression equations to estimate outflow volumes (Lane, Diskin, and Renard 1971) and simplified differential equations for loss rate as a function of channel length (Jordan 1977). Other, more complicated methods have also been used (Lane 1972, Wu 1972, Smith 1972, Peebles 1975).

Lane, Ferreira, and Shirley (1980) developed a procedure to relate parameters of the linear regression equations (Lane, Diskin, and Renard 1971) to a differential equation coefficient and the decay factor proposed by Jordan (1977). This linkage between the regression and differential equations provides the basis of the applications described in this chapter.

Empirical Basis of the Regression Equation

When observed inflow-outflow data for a channel reach of an ephemeral stream with no lateral inflow are plotted on rectangular coordinate paper, the result is often no outflow for small inflow events, with outflow increasing as inflow increases. When data are fitted with a straight-line relationship, the intercept on the X axis represents an initial abstraction. Graphs of this type suggest equations of the form

$$Q(x,w) = \begin{cases} 0 & P \leq P_o(x,w) \\ a(x,w) + b(x,w)P & P > P_o(x,w). \end{cases} \tag{19–1}$$

By setting $Q(x,w) = 0.0$ and solving for P, the threshold volume, the volume of losses that occur before outflow begins, is

$$P_o(x,w) = \frac{-a(x,w)}{b(x,w)}. \tag{19–2}$$

Differential Equation for Changes in Volume: Linkage With the Regression Model

Differential equations can be used to approximate the influence of transmission losses on runoff volumes. Because the solutions to these equations can be expressed in the same form as the regression equations, least-squares analysis can be used to estimate parameters in the transmission loss equations.

Unit Channel

The rate of change in volume, Q (as a function of arbitrary distance), with changing inflow volume, P, can be approximated as

$$\frac{dQ}{dx} = -c - k\,Q(x). \tag{19–19}$$

Substituting the initial condition and defining $P = Q(x = 0)$, the solution of equation 19–19 is

$$Q(x) = -\frac{c}{k}(1 - e^{-kx}) + Pe^{-kx}. \tag{19–20}$$

For a unit channel, equation 19–20 becomes

$$Q = -\frac{c}{k}(1 - e^{-k}) + Pe^{-k}, \tag{19–21}$$

which corresponds to the regression equation

$$Q = a + bP. \tag{19–22}$$

Equating equations 19–21 and 19–22, it follows that

$$b = e^{-k} \tag{19–11}$$

and

$$a = -\frac{c}{k}(1 - e^{-k}) = -\frac{c}{k}(1 - b) \tag{19–23}$$

are the linkage equations. Equation 19–23 can be solved for c as

$$c = -k\frac{a}{1 - b}.$$

Channel of Arbitrary Length and Width

For a channel of width w and length x,

$$\frac{dQ}{dx} = -wc - wkQ(x,w),$$

where $c = -k\frac{a}{1 - b}$, so that the differential equation is

$$\frac{dQ}{dx} = wk\frac{a}{1 - b} - wkQ(x,w).$$

Defining P as $Q(x = 0)$ and substituting this initial condition, the solution is

$$Q(x,w) = \frac{a}{1 - b}[1 - e^{-kxw}] + Pe^{-kxw}.$$

From the linkage

$$b(x,w) = e^{-kxw} \tag{19–13}$$

and

$$\begin{aligned} a(x,w) &= \frac{a}{1 - b}[1 - b(x,w)] \\ &= \frac{a}{1 - b}[1 - e^{-kxw}], \end{aligned} \tag{19–14}$$

where a and b are unit channel parameters and k is the decay factor.

Influence of Uniform Lateral Inflow

If Q_L is the uniform lateral inflow (acre-feet per mile), this inflow becomes an additional term in the differential equation

$$\frac{dQ}{dx} = wk\frac{a}{1 - b} - wkQ(x,w) + Q_L.$$

The solution is

$$Q(x,w) = \frac{a}{1 - b}[1 - e^{-kxw}] + Pe^{-kxw} + \frac{Q_L}{kw}[1 - e^{-kxw}],$$

and through the linkage, the outflow volume equation for upstream inflow augmented by uniform lateral inflow is

$$Q(x,w) = a(x,w) + b(x,w)P + \frac{Q_L}{kw}[1 - b(x,w)]. \qquad (19\text{–}4)$$

Approximations for Peak Discharge

The basic assumption for peak discharge, q(x,w), is that the outflow peak, once an average loss rate has been subtracted, is equal to b(x,w) times the peak of the inflow hydrographs, p. That is, assume that

$$q(x,w) = -\frac{P - Q(x,w)}{D} + b(x,w)p,$$

where $P - Q(x,w) = -a(x,w) + [1 - b(x,w)]P$, so that

$$q(x,w) = \frac{12.1}{D}(a(x,w) - [1 - b(x,w)]P) + b(x,w)p, \qquad (19\text{–}3)$$

where D is the mean duration of flow and 12.1 converts acre-feet per hour to cubic feet per second. For a peak lateral inflow rate of q_L (cfs/ft), uniform along the reach, the peak discharge equation becomes

$$q(x,w) = \frac{12.1}{D}(a(x,w) - [1 - b(x,w)]P) + b(x,w)p + \frac{q_L(5{,}280)}{kw}[1 - b(x,w),$$

where 5,280 converts cubic feet per second per foot to cubic feet per second per mile.

For small inflows, where the volume of transmission losses is about equal to the volume of inflow, the peak discharge equation, equation 19–3, overestimates the peak rate of outflow. The relation between peak rate of outflow observed and that computed from equation 19–3 is shown in figure 19–1. The bias shown in figure 19–1 is for small events and tends to overpredict, but the equation does well for the larger events. The computed values shown in figure 19–1 were based on the mean duration of flow for each channel reach. Better agreement of predicted and observed peak rates of outflow might be obtained by using actual flow durations.

Appendix 2—Analysis of Selected Data Used to Develop the Procedure for Estimating Transmission Losses

So that parameters of the prediction equations could be related to hydrograph characteristics and to effective hydraulic conductivity, it was necessary to analyze selected data. Events involving little or no lateral inflow were selected from channel reaches in Arizona, Kansas, Nebraska, and Texas (table 19–5).

The data shown in table 19–5 are not entirely consistent because the events were floods of different magnitudes. The Walnut Gulch data are from a series of small to moderate events representing in-bank flow, whereas the Queen Creek data are for relatively larger floods and no doubt include some out-of-bank flow. The Trinity River data represent pumping diversions entirely within the channel banks. Data for the Kansas-Nebraska streams represent floods of unknown size, and may include out-of-bank flow.

The data summarized in table 19–5 were subjected to linear regression analysis to estimate the parameters a(x,w), b(x,w), $P_o(x,w)$, and kxw. These parameters are summarized in table 19–6. Parameters for the unit channels were computed for 10 channel reaches and are shown in table 19–7.

Appendix 3.—Estimating Transmission Losses When No Observed Data Are Available

Estimating transmission losses when observed inflow-outflow data are not available requires a technique for using effective hydraulic conductivity to develop parameters for the regression analysis.

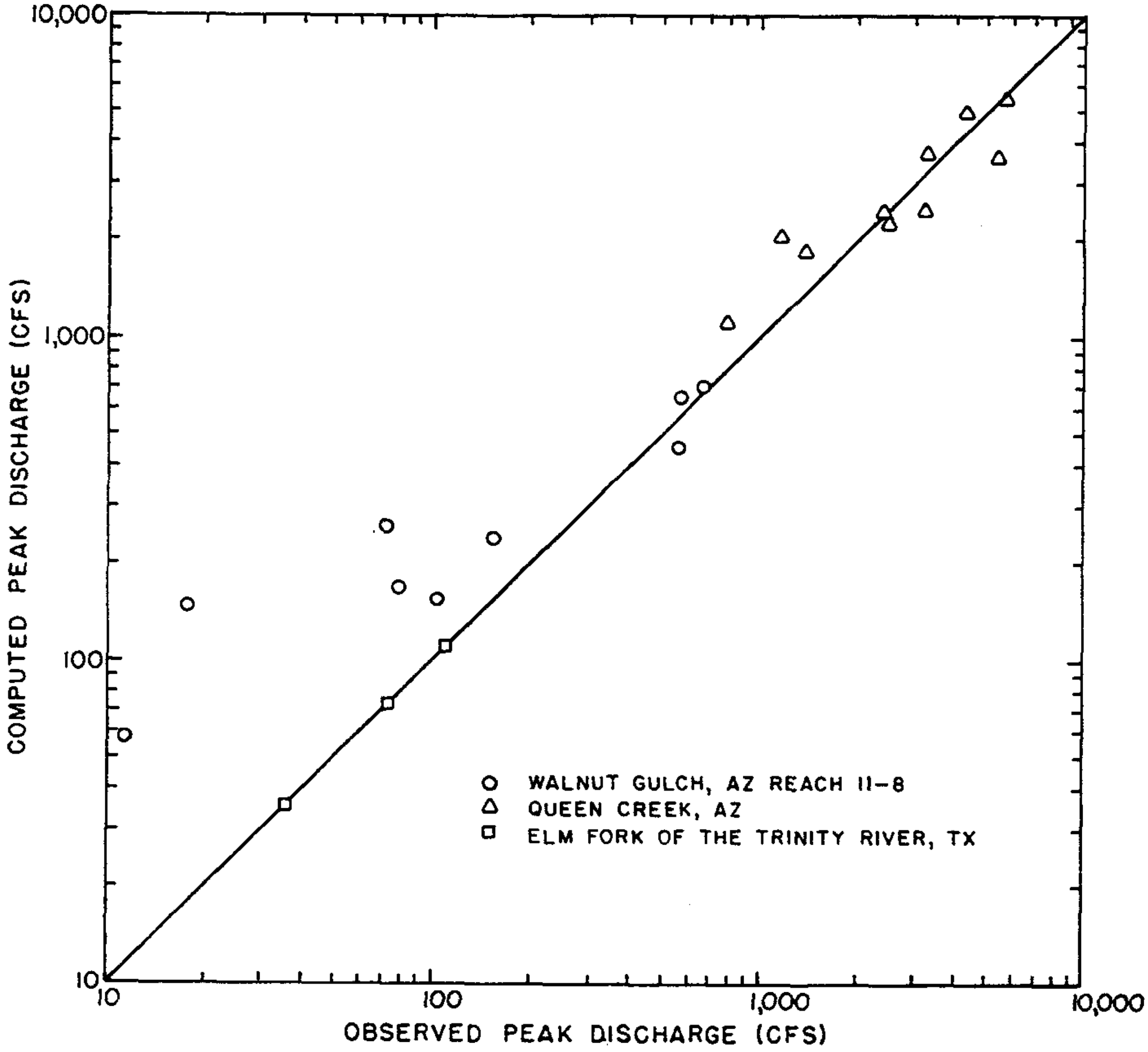

Figure 19–1.—Observed vs. computed peak discharge of the outflow hydrograph.

Table 19-5.—Hydrologic data used in analyzing transmission losses (Lane et al. 1980)

Location	Reach identification	Length, x	Average width, w	Number of events	Inflow volume		Outflow volume	
					Mean	Standard deviation	Mean	Standard deviation
		mi	*ft*		*acre-ft*	*acre-ft*	*acre-ft*	*acre-ft*
Walnut Gulch, Ariz.[1]	11-8	4.1	38	11	16.5	14.4	8.7	11.4
	8-6	0.9	—	3	13.7	—	11.4	—
	8-1	7.8	—	3	16.3	—	1.6	—
	6-2	2.7	107	30	75.1	121.6	59.9	101.0
	6-1	6.9	121	19	48.3	51.7	17.1	26.5
	2-1	4.2	132	32	49.3	42.7	24.4	31.4
Queen Creek, Ariz.[2]	Upper to lower gaging station	20.0	277	10	4,283	5,150	2,658	3,368
Elm Fork of Trinity River, Tex.[3]	Elm Fork-1	9.6	—	3	454	—	441	—
	Elm Fork-2	21.3	—	3	441	—	424	—
	Elm Fork-3	30.9	120	3	454	—	424	—
Kansas-Neb.[4]	Prairie Dog	26.0	17	5	1,890	1,325	1,340	1,218
	Beaver	39.0	14	7	2,201	2,187	1,265	1,422
	Sappa	35.0	23	6	6,189	8,897	3,851	7,144
	Smokey Hills	47.0	72	4	1,217	663	648	451

[1] Data on file at USDA-ARS, Southwest Rangeland Water Research Center, 442 E. 7th Street, Tucson, AZ 85705.
[2] Data from Babcock and Cushing (1941).
[3] Data from the Texas Board of Water Engineers (1960).
[4] Data from Jordan (1977).

Table 19-6.—Parameters for regression model and differential equation model for selected channel reaches (Lane et al. 1980)

Location	Reach identification	Reach no.	Length, x	Average width, w	Regression intercept, a(x,w)	Model slope, b(x,w)	Threshold volume, $P_o(x,w)$	Decay factor, kxw	R^2
			mi	*ft*	*acre-ft*	*acre-ft*			
Walnut Gulch, Ariz.	11-8	1	4.1	38	−4.27	0.789	5.41	0.2370	0.98
	8-6	2	0.9	—	−0.34	0.860	0.40	0.1508	.99
	8-1	3	7.8	—	−2.38	0.245	9.71	1.4065	.84
	6-2	4	2.7	107	−4.92	0.823	5.98	0.1948	.98
	6-1	5	6.9	121	−5.56	0.469	11.86	0.7572	.84
	2-1	6	4.2	132	−8.77	0.673	13.03	0.3960	.84
Queen Creek, Ariz.	Upper to lower station	7	20.0	277	−117.2	0.648	180.90	0.4339	.98
Elm Fork of Trinity River, Tex.	Elm Fork-1	8	9.6	—	−15.0	[1]1.004	—	—	.99
	Elm Fork-2	9	21.3	—	[1]+7.6	0.944	—	—	.99
	Elm Fork-3	10	30.9	120	−8.7	0.952	9.14	0.0492	.99
Kansas-Nebraska	Prairie Dog	11	26.0	17	−353.1	0.896	394.10	0.1098	.95
	Beaver	12	39.0	14	−157.3	0.646	243.50	0.4370	.99
	Sappa	13	35.0	23	−1,076.3	0.796	1,352.10	0.2282	.98
	Smokey Hills	14	47.0	72	−99.1	0.614	161.40	0.4878	.81

[1] Channel reaches where derived regression parameters did not satisfy the constraints.

Table 19–7.—Unit length, unit width, and unit length and width parameters for selected channel reaches (Lane et al. 1980)

Location	Identification	Unit length parameters			Unit width parameters			Unit length and width parameters			
		a(w)	b(w)	$P_o(w)$	a(x)	b(x)	$P_o(x)$	a	b	P_o	k
Walnut Gulch, Ariz.	11–8	−1.13657	0.94384	1.2042	−0.12587	0.99378	0.1267	−0.03076	0.998480	0.0308	0.001521
	6–2	−1.93484	0.93039	2.0796	−0.05059	0.99818	0.0507	−0.01874	0.999326	0.0187	0.000674
	6–1	−1.08819	0.89607	1.2144	−0.06541	0.99376	0.0658	−0.00950	0.999094	0.0095	0.000907
	2–1	−2.41320	0.91002	2.6518	−0.08046	0.99700	0.0807	−0.01915	0.999286	0.0192	0.000714
Queen Creek, Ariz.	Upper to lower station	−7.14508	0.97854	7.3018	−0.52273	0.99843	0.5236	−0.02597	0.999922	0.0260	0.0000783
Trinity River, Tex.	Elm Fork–3	−0.28825	0.99841	0.2887	−0.07427	0.99959	0.0743	−0.002404	0.999987	0.0024	0.0000133
Kansas-Nebraska	Prairie Dog	−14.30986	0.99579	14.3705	−21.86124	0.99356	22.0029	−0.842008	0.999752	0.8422	0.000248
	Beaver	−4.95071	0.98886	5.0065	−13.65447	0.96927	14.0874	−0.355480	0.999200	0.3558	0.000800
	Sappa	−34.28091	0.99350	34.5052	−52.07808	0.99013	52.5972	−1.493102	0.999717	1.4935	0.000283
	Smokey Hills	−2.65060	0.98968	2.6782	−1.73337	0.99325	1.7451	−0.036970	0.999856	0.0370	0.000144

Estimating Effective Hydraulic Conductivity

The total volume of losses for a channel reach is KD, where K is the effective hydraulic conductivity and D is the duration of flow. Also, the total losses are P − Q(x,w), so that

$$KD = 0.0275[P - Q(x,w)],$$

where 0.0275 converts acre-feet per foot-mile-hour to inches per hour. Or, solving for K,

$$K = \frac{0.0275\,[P - Q(x,w)]}{D}.$$

But

$$P - Q(x,w) = -a(x,w) + [1 - b(x,w)]P,$$

so that

$$K = \frac{0.0275}{D}[-a(x,w) + [1 - b(x,w)]P] \qquad \textbf{(19–24)}$$

is an expression for effective hydraulic conductivity. If mean values for D and P are used, then equation 19–24 estimates the mean value of the effective hydraulic conductivity.

Effective Hydraulic Conductivity vs. Model Parameters

For a unit channel, outflow is the difference between inflow and transmission losses:

$$Q = P - KD.$$

Because Q = a + bP,

$$-a + (1 - b)P = KD.$$

But because a and (1 − b)P are in acre-feet and KD, the product of conductivity and duration, is in inches, the dimensionally correct equation is

$$-a + (1 - b)P = 0.0101KD,$$

where 0.0101 converts inches over a unit channel to acre-feet. Because this equation is in two unknowns (a and b), an additional relationship is required to solve it. As a first approximation, the total losses are partitioned between the two terms in the equation. That is, let

$$a = -\alpha(0.0101KD)$$

and

$$(1 - b) = (1 - \alpha)\left(0.0101\frac{KD}{P}\right).$$

Solving for b,

$$b = 1 - (1 - \alpha)\left(0.0101\frac{KD}{P}\right),$$

where $0 \leqslant \alpha \leqslant 1$ is a weighting factor. Solve for k by substituting $b = e^{-k}$ and taking the negative natural log of both sides, i.e.,

$$k = -\ln\left[1 - (1 - \alpha)\left(0.0101\frac{KD}{P}\right)\right].$$

The selected data were analyzed to determine α by least-squares fitting as shown in table 19–8. For the data shown in table 19–8, the estimate of α was 0.46. Figures 19–2 and 19–3 show the data in table 19–8 plotted according to the equations

$$a = -0.00465KD \qquad \textbf{(19–15)}$$

and

$$k = -1.09\ln\left[1 - 0.00545\frac{KD}{P}\right], \qquad \textbf{(19–16)}$$

where for each channel reach, mean values were used for K, D, and P. These relationships were used to calculate the values shown in table 19–1.

Auxiliary data compiled in a report by Wilson et al. (1980) are shown in table 19–9. Although the estimates of infiltration rates were obtained by a variety of methods, most rates were based on streamflow data. Because these estimates generally involved longer periods of flow than in the smaller ephemeral streams, they should be representative of what is called effective hydraulic conductivity. The data show the range of estimates of hydraulic conductivity for various streams within a river basin as estimated by several investigators. For this reason, they should be

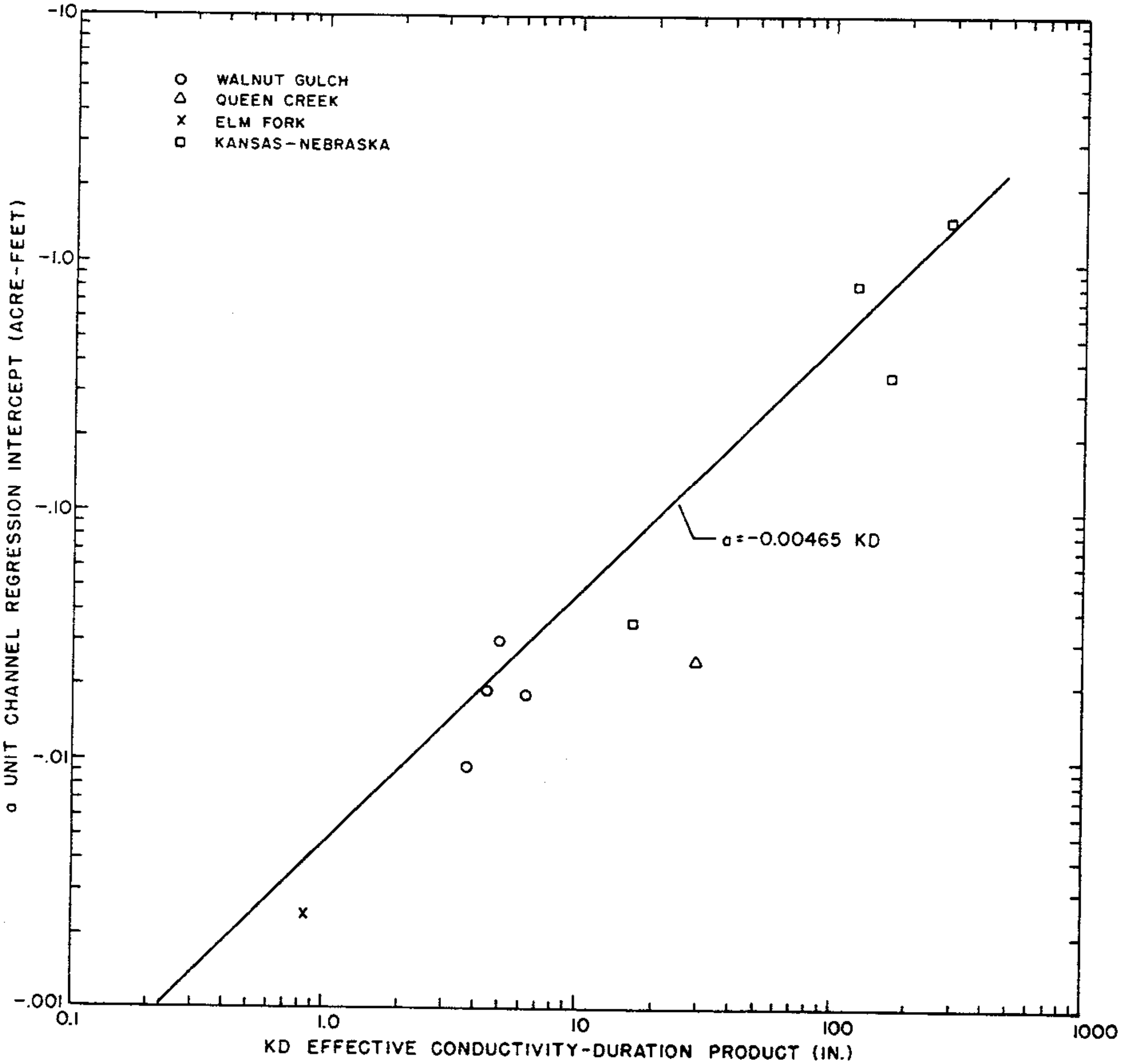

Figure 19–2.—Relation between KD and regression intercept.

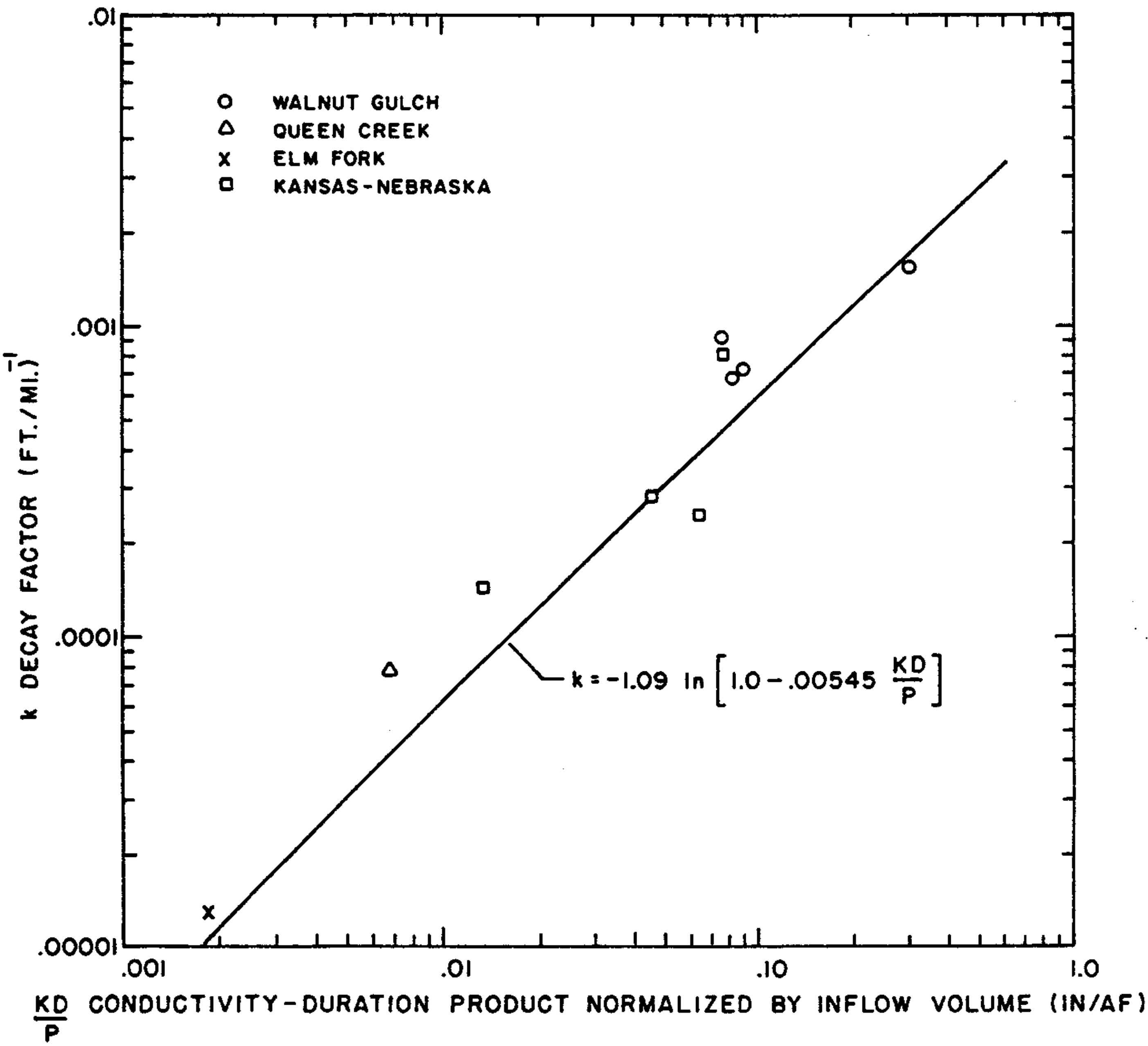

Figure 19-3.—Relation between KD/P and decay factor.

Table 19–8.—Data for analysis of relations between effective hydraulic conductivity and model parameters (Lane et al. 1980)

Location	Unit channel intercept, a	Decay factor, k	K	KD	$\frac{KD}{P}$	$-\ln\left[1 - 0.00545\frac{KD}{P}\right]$	Comments
	acre-ft	*(ft-mi)$^{-1}$*	*in/hr*	*in*	*in / acre-ft*		
Walnut Gulch							
11–8	−0.03076	0.001521	1.55	4.96	0.3010	0.001643	In-bank flow
6–2	−0.01874	0.000674	1.36	6.26	0.0834	0.000455	
6–1	−0.00950	0.000907	1.03	3.71	0.0768	0.000419	
2–1	−0.01915	0.000714	1.11	4.44	0.0901	0.000492	
Queen Creek	−0.02597	0.0000783	0.54	29.16	0.0068	0.0000371	Mixed flow
Elm Fork	−0.00240	0.0000133	0.01	0.84	0.0019	0.0000104	In-bank flow
Kansas-Nebraska							
Prairie Dog	−0.84201	0.000248	1.28	122.9	0.0650	0.000355	Mixed flow:
Beaver	−0.35548	0.000800	1.38	169.7	0.0771	0.000421	average widths
Sappa	−1.49310	0.000283	2.57	287.8	0.0465	0.000254	may be under-
Smokey Hills	−0.03697	0.000144	0.17	16.3	0.0134	0.000073	estimated

Least-squares fit:

$$a = -0.00465KD$$

$$k = -1.09 \ln\left[1 - 0.000545\frac{KD}{P}\right]$$

Table 19–9.—Auxiliary transmission-loss data for selected ephemeral streams in southern Arizona (data taken from Wilson et al. [1980])

River basin	Stream reach	Estimation method	Effective hydraulic conductivity	Source of estimates
			in/hr	
Santa Cruz	Santa Cruz River, Tucson to Continental	Streamflow data[1]	1.5–3.4	Matlock (1965)
	Santa Cruz River, Tucson to Cortero	Streamflow data	3.2–3.7	Matlock (1965)
	Rillito Creek, Tucson	Streamflow data	0.5–3.3	Matlock (1965)
	Rillito Creek, Cortero	Streamflow data	2.2–5.5	Matlock (1965)
	Pantano Wash, Tucson	Streamflow data	1.6–2.0	Matlock (1965)
	Average for Tucson area	—	1.65	Matlock (1965)
Gila	Queen Creek	Streamflow data:		
		Summer flows	0.07–0.52	Babcock and Cushing (1942)
		Winter flows	0.37–1.05	Babcock and Cushing (1942)
		Average for all events	0.54	Babcock and Cushing (1942)
		Seepage losses in pools[2]	>2.0	Babcock and Cushing (1942)
	Salt River, Granite Reef Dam to 7th Avenue	Streamflow data	0.75–1.25	Briggs and Werho (1966)
San Pedro	Walnut Gulch	Streamflow data	1.1–4.5	Keppel (1960), Keppel and Renard (1962)
	Walnut Gulch	Streamflow data	2.4	Peebles (1975)
San Simon	San Simon Creek	—	0.18	Peterson (1962)

[1] Transmission losses estimated from streamflow data.
[2] Measurement of loss rates from seepage in isolated pools.

viewed as qualitative estimates. Improved estimates based on site-specific conditions were used in developing the prediction equations.

For comparison, seepage loss rates for unlined canals are shown in table 19–10. Though these data are not strictly comparable with loss rates in natural channels, they do show the variation in infiltration rates with different soil characteristics. Infiltration rates varied by a factor of over 20 (0.12–3.0 in/hr) from a clay loam soil to a very gravelly soil.

Table 19–10.—Range of seepage rates in unlined canals (data taken from Wilson et al. [1980] after Kraatz [1977])

Effective hydraulic conductivity	Description of materials[1]
in/hr	
0.12–0.18	Clay-loam, described as "impervious"
0.25–0.38	Ordinary clay loam
0.38–0.50	Sandy loam or gravelly clay-loam with sand and clay
0.50–0.75	Sandy loam
0.75–0.88	Loose sandy soil
1.0–1.25	Gravelly sandy soils
1.5–3.0	Very gravelly soils

[1] Does not reflect the flashy, sediment-laden character of many ephemeral streams.

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